2018

Economic Operation Optimization of Battery Energy Storage Systems in a Solar Rich Microgrid

Herath Pathiranage Asanga Priyankara Jayawardana
University of Wollongong, hpapj953@uowmail.edu.au

Massimo Fiorentini
University of Wollongong, massimo@uow.edu.au

Duane A. Robinson
University of Wollongong, duane@uow.edu.au

Ashish P. Agalgaonkar
University of Wollongong, ashish@uow.edu.au

Abstract

The increasing trend of connecting local distributed generation units to the grid has unlocked new economic opportunities for owners. This is supported by the ongoing development of energy storage technologies, especially battery based systems. In practice, battery storage systems typically operate based on control algorithms where tariff structures and future generation and load profiles are not taken into account. This paper investigates the results of a case study for a microgrid using a proposed optimization model which minimizes cost by considering an import/export tariff structure. The effect of changing time resolution related to variations in demand and generation is examined, and the model assesses economic considerations related to operational capabilities of the battery energy storage.

Keywords

microgrid, solar, economic, operation, optimization, battery, storage, rich, systems, energy

Disciplines

Engineering | Science and Technology Studies

Publication Details

H. P.A.P. Jayawardana, M. Fiorentini, D. A. Robinson & A. P. Agalgaonkar, "Economic Operation Optimization of Battery Energy Storage Systems in a Solar Rich Microgrid," in CIRED Workshop on Microgrids and Local Energy Communities, 2018, pp. 0435-1-0435-5.

ECONOMIC OPERATION OPTIMISATION OF BATTERY ENERGY STORAGE SYSTEMS IN A SOLAR RICH MICROGRID

H.P.A.P. JAYAWARDANA Massimo FIORENTINI Duane A. ROBINSON Ashish P. AGALGAONKAR
University of Wollongong, NSW 2522, Australia
hpapj953@uowmail.edu.au

ABSTRACT

The increasing trend of connecting local distributed generation units to the grid has unlocked new economic opportunities for owners. This is supported by the ongoing development of energy storage technologies, especially battery based systems. In practice, battery storage systems typically operate based on control algorithms where tariff structures and future generation and load profiles are not taken into account. This paper investigates the results of a case study for a microgrid using a proposed optimisation model which minimizes cost by considering an import/export tariff structure. The effect of changing time resolution related to variations in demand and generation is examined, and the model assesses economic considerations related to operational capabilities of the battery energy storage.

INTRODUCTION

Microgrids are an upcoming concept in the electricity industry. Although there are few operational microgrids around the world, this concept is further reinvigorated by the fast growing connection of distribution generation units to the electricity grid, especially in the form of solar photovoltaic (PV) systems. Connection of combined rooftop solar PV systems and battery storage systems in domestic and commercial premises has also broadened the microgrid concept [1]. With the applicability of microgrids growing, it is important to investigate the feasibility of renewable rich microgrids as the cost for these technologies is still high for small scale investors.

According to [2], battery storage systems are mainly utilized for renewable capacity framing, electric energy time shifting and bill management. However, these applications demand for certain pre-defined control algorithms, where the battery storage system is controlled in a continuous manner with a limited number of inputs. Most of these control algorithms are based on excess electrical energy and state-of-charge (SOC) of the battery, where the battery storage system is charged or discharged depending on the availability of the excess electrical energy and the capacity of the battery storage system [3]. However, moving away from standard control methods, the need for optimised operation of battery storage systems is still being investigated [4]. The ability to reduce the cost of electrical energy using the optimised operation of a self-contained battery storage system in a microgrid is one of the main challenges, and demands due consideration of tariff structures [5]. This will provide impetus for the participation of renewable based microgrids in the grid as customer benefits are secured with optimised operation of battery storage [6].

In the literature, most of the optimisation/analyses have been carried out for 1 hour time intervals [7]. Few studies investigate the effect of varying time intervals on optimisation outcomes. This is vital for any optimisation study which takes future parameters or variables into account. Also, there is still a potential to use different charging/discharging rates to gain maximum benefits from renewable rich microgrids.

This paper analyses the relationships between economic operation of battery energy storage systems and the varying resolution of demand and generation data. Also, the effect of charging/discharging rates and capabilities of the battery storage system are assessed. This work is based on a hybrid model, developed using hybrid system description language (HYSDEL), which is optimised using a model predictive controller (MPC) developed using the multi-parametric toolbox (MPT) [8]. The controller was simulated both in open loop with a perfect prediction of the future disturbances, and in closed loop.

The paper is structured as follows: (i) description of the proposed system model, used for all the analyses; (ii) comprehensive analysis of case study results, which highlights the relationship between varying resolution of data and charging/discharging rates of a battery storage system; and (iii) conclusions of the paper.

PROPOSED SYSTEM MODEL

The proposed system model is based on the Sustainable Buildings Research Centre microgrid at the University of Wollongong. The single line diagram of the microgrid is shown in Fig. 1, which comprises of 166.5 kWp of solar PV generation connected to local loads. It is assumed a 100 kWh lithium-ion battery storage system is integrated in the microgrid [9]. Furthermore, utility supply is provided through the point of common coupling for import/export of electrical energy.

The utility tariff structure is considered to be a flat tariff, where import and export energy rates are constant throughout the day at AUD$0.12/kWh and AUD$0.05/kWh respectively [10]. The flat tariff structure reduces the complexity of the model and provides a benchmark for exploring future feasible tariff schemes. It is assumed the SOC level at the beginning of each analysis is 100% and the minimum SOC is 20%.

The primary objective of the model is to identify a

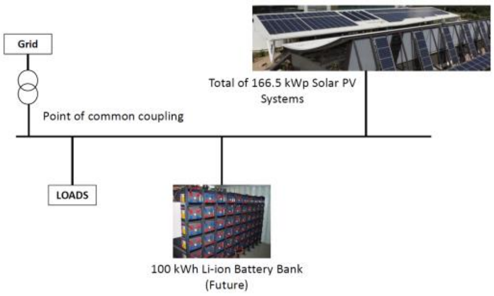

Figure 1. Test microgrid under study.

charging/discharging pattern which optimises the electrical energy cost for the microgrid. In order to achieve this, a model predictive control strategy was developed using HYSDEL and MPT, which are run in MATLAB. The following state space model was implemented in HYSDEL. The state variable x represents the energy stored in the battery while the output y is the net energy cost for the microgrid (positive in the case of energy import and negative in the case of energy export).

$$\dot{x} = Ax + Bu$$

where $A = 1$, $B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$ and $u = \begin{bmatrix} P_{PV} \\ P_L \\ P_{ESS} \end{bmatrix}$

P_{PV} – Generated power from PV
P_L – Loads to be supplied in the microgrid
P_{ESS} – Charging(+ve)/discharging(-ve) from the battery

$$P_{grid} = P_{PV} + P_L + P_{ESS}$$

Depending on the value of P_{grid}, the import/export power from the grid, the associated cost calculations are made either using the import or export tariff. This is done using a binary variable δ which is 0 or 1 depending on P_{grid}.

$$\delta = 1 \text{ if } P_{grid} > 0 \quad \delta = 0 \text{ if } P_{grid} < 0$$

$$y = Cx + D_1 u \quad \text{when } \delta = 1$$
$$y = Cx + D_2 u \quad \text{when } \delta = 0$$

Where $C = 0$; and D_1 and D_2 are import and export tariff rates respectively.

HYSDEL is capable of modelling logical systems using a mathematical representation [11]. In the MPC, it is necessary to define the following cost function and the length of the control and prediction horizon [12]. In this study, the control and prediction horizons were considered to be equal. Also, P equals 1 while Q and R are both set to zero.

$$min_{\{u\}_0^{N-1}} J = \sum_{k=1}^{N-1} \|Q(x(k) - x_r)\|_p + \|R(u(k) - u_r)\|_p$$

Where,
p - Linear norm, can be 1 or Inf for 1- and Infinity-norm, respectively
Q - Weighting matrix on the states
R - Weighting matrix on the manipulated variables

After devising a mathematical model using HYSDEL, MPT was used to solve the model using CPLEX solver. The results of the optimisation algorithm were verified using different methods such as 'brute force' approach and sensitivity analysis. The model also accounts for cost associated with the charging/discharging of the battery, and therefore its degradation. A null charging and discharging of the battery leads to a very large number of optimal solutions, which can be unreasonable due to higher usage of the battery (quick degradation). In order to account for the finite life and hence, charge/discharge cycles of the battery, the cost for charging/discharging is considered to be AUD$0.01/kWh in all the simulated scenarios.

CASE STUDY AND ANALYSES

1 hour time interval

For the preliminary analysis, 1 hour time intervals are considered. Fig. 2 shows the results for the charging and discharging pattern when the 24 hour control horizon is selected and the open loop optimisation analysis is conducted. In the open loop analysis, the optimal cost value can be obtained for a particular day. However, this will not consider any future (day ahead) generation or load. Even though the controllability increases when 1 hour time interval is selected, the changes related to solar PV generation or load profile in each 1 hour energy block are extensive and need to be considered.

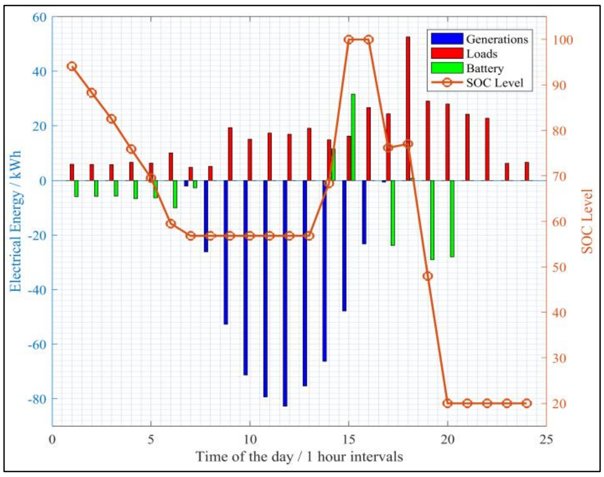

Figure 2. Results for one hour open loop optimisation.

Time intervals of 30, 15, 10 and 5 minutes

In these simulations, the total energy generated, consumed, charged or discharged is considered in an aggregated manner as an average energy in that time step without considering any intermittent variations. When the time step is 1 hour, this can have a significant effect. However, the capabilities of the battery storage system to handle these variations may change the optimised cost value and the usage of the battery storage system. In order to analyse this particular aspect, the time step of the optimisation model was modified.

The generation and load profiles were modified keeping the total generation and load to the same level for each

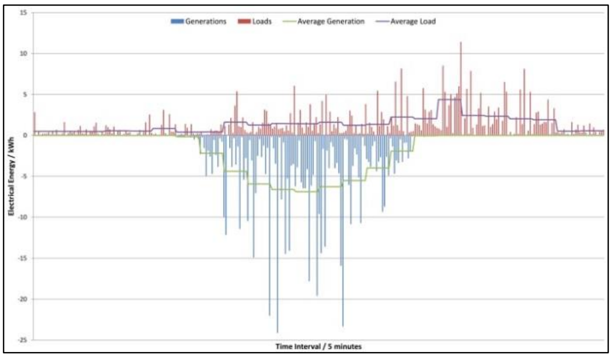

Figure 3. Generation and load profiles with 5 min resolution

1 hour block. The time intervals are changed from 60 min to 30 min, 15 min, 10 min and 5 min. Fig. 3 shows obtained generation and load profiles for 5 min resolution. For each of the time intervals, the charging/discharging rate of the battery storage is maintained at 40 kW, i.e. 40 kWh/h, 20 kWh/30min, 10 kWh/15min, 6.6 kWh/10min and 3.3 kWh/5min respectively. The effect of charging/discharging rate on the optimal cost value and the battery usage was also investigated.

The open loop analysis was undertaken to investigate the relationship between the resolution of data or time step size and the optimal cost and the usage of the battery storage system. Table 1 summarizes the optimal cost and usage of the battery storage for different optimisation time steps.

Table 1. Results of Open Loop Analyses

Time Step	$SOC_{(end)}$	Usage (kWh)	Cost (AUD)	Grid (kWh)
1 hour	0.2	168.0	-1.04	-217.8
30 min	0.2	174.4	-0.24	-217.8
15 min	0.2	255.7	-0.68	-217.8
10 min	0.2	195.9	0.50	-217.8
5 min	0.2	236.8	-0.18	-217.8

Usage of the battery storage is considered as the total energy charged and discharged to/from the battery at the end of the day. According to the Table 1, it can be seen that the optimal cost increases while the usage shows a random variation from 1 hour to 5 min. Other than at 15 min and 1 hour, which show maximum and minimum usage respectively, battery usage remains at a similar order of magnitude. This variation of optimal cost value and the battery usage can be due to the increase of the control horizon as the number of time steps increases. However, the open loop analyses cannot justify the importance of using high resolution data unless the results are compared against the results of closed loop analyses. Therefore, closed loop analyses, where feedback is provided after the specified time step, are carried out considering same generation and load profiles ahead, no generation ahead and different profiles for generation and load (same total as indicated earlier) ahead. During the closed loop analysis, generation and load profiles of the next day are considered to remain the same without adjusting to any forecasting errors. This will be addressed later in this section.

Fig. 4 and Fig. 5 indicate the variation of the cost, usage of the battery and the SOC for each time step. These results confirm that the time step of the optimisation affects the optimal value of cost. But, these optimal cost values should be compared with the final SOC levels. The optimal cost value and SOC level are higher for a time step of 5 min as compared to other time step values. The other factor, which should be considered, is the usage of the battery storage. According to the results, increment of the usage is comparatively lower until the 10 min step.

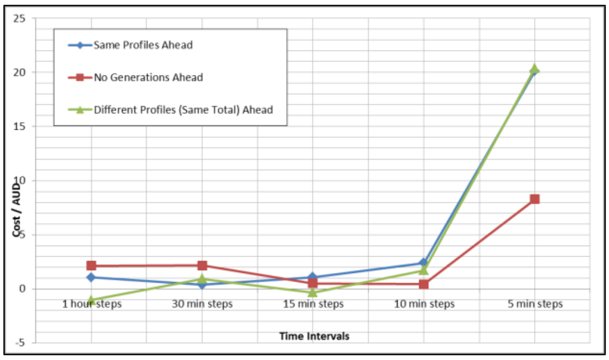

Figure 4. Variation of optimal cost values with different time steps

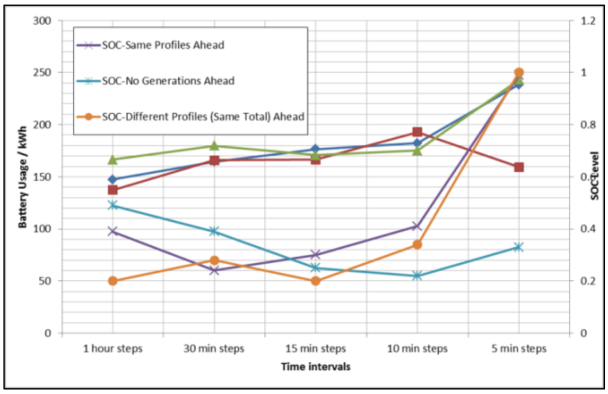

Figure 5. Variation of battery usage and SOC level with different time steps

Importantly, time to solve these closed loop optimisation for a complete day increases exponentially as the time step becomes smaller. If the closed loop is executed in a continuous mode where the solutions are obtained only for one control horizon (say 24 hours), the solution time will be significantly lower. Considering all the factors, it can be concluded that the time step of the optimisation affects the optimal solution. As mentioned earlier, if the future generations are set to change with the continuous predictions then the values of the lower time steps can be more realistic as the prediction error can be minimal.

Fig. 6 illustrates the charging/discharging pattern and

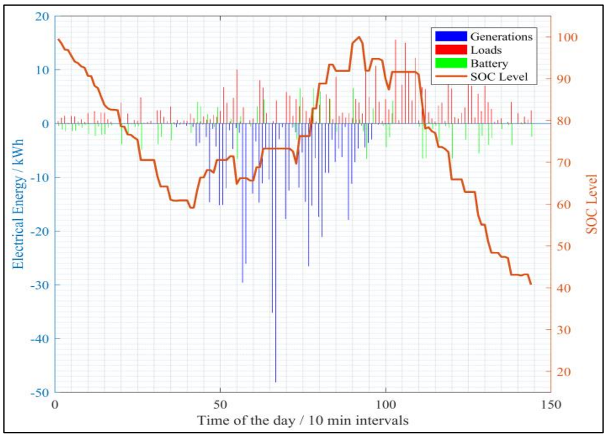

Figure 6. Results of closed loop (same profile ahead) optimisation for 10 min time intervals

the SOC level variation when the closed loop optimisation is implemented. In this case, the next day is assumed to have the same generation and load profiles. In the closed loop analysis the model takes into account future generation and load values. Therefore, a higher value of the SOC level can be observe at the end of the day compared to open loop 10 min analysis. In this way the battery storage system is kept prepared for the next day.

Effect of charging/discharging rate

For all the above analyses, the charging/discharging rate was maintained at 40 kW. For example the battery storage considered in this case study can be charged/discharged at a rate of 40 kWh per hour and for 15 min it is considered to be charged/discharged 10 kWh. However, the ability for fast charging/discharging in the innovative battery storage systems enables the optimisation models to vary the charging/discharging rate within the small time steps. Hence, the relationship between the charging/discharging rates and optimal cost value needs to be examined. For this particular analysis, open loop and closed loop (same profiles ahead) controls with a 10 min time step were undertaken. The charging and discharging rates remain equal and changed from 1 kW to 40 kW before obtaining the optimal cost and usage value for the battery storage system.

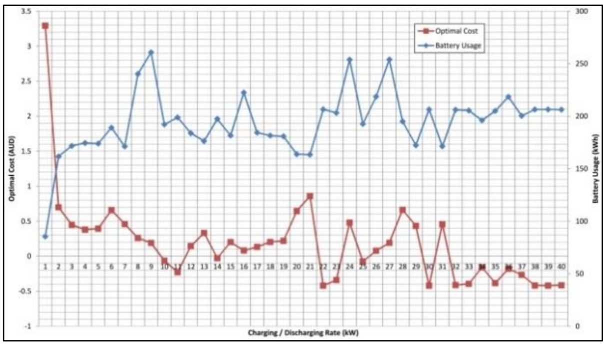

Figure 7. Variation of optimal cost values and the battery usage with different charging/discharging rates in open loop

Fig. 7 shows the results obtained from the open loop optimisation analysis. It can be seen that the optimal cost is affected by varying the charging/discharging rate in a random manner between the 6 kW and 38 kW range. However, the optimal cost is spread over a smaller range. This indicates that the charging/discharging rates of the battery storage may not contribute to the optimal cost in a significant manner for this case study. To investigate this further, a closed loop optimisation with same profile ahead was undertaken and the results are shown in Fig. 8. This again confirms the effect of the charging/discharging rate on the optimal value is not significant, as the results vary randomly near the optimal cost value. However, an important point in relation to open loop and closed loop optimisation analyses is that there are lower cost values after the charging/discharging rate of 6.6 kW, which is the set value for the 10 min time step optimisation. This indicates that an optimal charging/discharging rate, which contributes to an optimal cost value can be calculated using the optimisation algorithm.

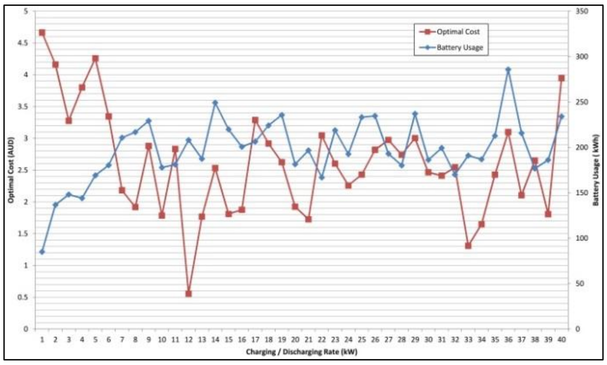

Figure 8. Variation of optimal cost values and the battery usage with different charging/discharging rates in closed loop

It is important to note the behaviour of the usage of the battery storage in both open loop and closed loop analyses, which shows an inverse pattern of the optimal cost. However, it may not derive any direct relationship with the battery usage and the optimal cost as there is a cost associated with the charging/discharging of the battery storage.

Feasibility of real time optimisation

It is necessary to research the capabilities of using optimisation in a real time controller. Firstly, the closed loop optimisation was set up for a continuous run with a control horizon of one day ahead. Within this control horizon, the optimisation is undertaken and the charging/discharging amount related to the considered time step sent to the battery storage management system. In parallel, the updated generation and load profiles for every time control horizon ahead are acquired. For this, generation and load prediction algorithms can be used. This will be more accurate if the time step is lower, as the accuracy of predictions are higher for smaller time steps.

Table 2. Solution Times for Different Time Steps

Time Step	Model Initialization Time (S)	Closed Loop Solution time (S)
1 hour	34.6	1.2
30 min	46.3	1.3
15 min	94.3	1.2
10 min	146.6	1.3
5 min	474.2	1.9

The time frame associated with executing closed loop optimisation can be calculated for different time steps. Table 2 summarizes the results. It is important to note the model initialization time, which is a one off time to convert the HYSDEL model to MPT and their associated matrices. As the number of data points increase, a significant increment of the model initialization time can be noticed. However, this is only at the start of the controller and no effect is there for the continuous operation.

These analyses were carried out using MPT 3.0 and MATLAB R2016a on a PC with Windows 7, Intel(R) Core(TM) i7 CPU 870 @ 2.93 GHz processor and an installed memory (RAM) of 8 GB.

Considering all the solution times, it can be noted that the optimisation can be performed for any of the above time steps. Model initiation time needs to be accounted only at the beginning of the optimisation. By considering the case study outcomes, a suitable time step can be selected for the real time controller.

CONCLUSION

The aim of this paper was to investigate the feasibility of renewable rich microgrids by investigating the relationship between the time interval of an optimisation model and charging/discharging rates of the battery storage system. A HYSDEL based optimisation model has been developed and the results are obtained for different cases. The results emphasize the importance of the time resolution in the optimisation formulation, in order to obtain more accurate results, while satisfying other factors such as usage and SOC levels of the battery energy storage. This has been confirmed from the case study results where 10 min analysis has become the most effective time interval considering all above aspects. Subsequently, further investigations have been carried out to find out the effects of the charging/discharging rates on the optimal cost values and this particular investigation has identified that the optimisation can identify further optimal cost values if the battery storage is capable of handling charging/discharging rate in a wide range, not limiting to a narrow band when the optimisation time interval is scaled down. The proposed optimisation including associated considerations related to the battery storage system can contribute to gain more benefits for the microgrid customers.

ACKNOWLEDGMENT

This research has been conducted with the support of the Australian Government Research Training Program Scholarship.

REFERENCES

[1] N. Hatziargyriou, H. Asano, R. Iravani, C. Marnay, “Microgrids”, *IEEE Power and Energy Magazine*, vol. 5, pp. 78-94, 2007.
[2] Office of Electricity Delivery & Energy Reliability, “DOE Global Energy Storage Database”, Available: http://www.energystorageexchange.org, [Accessed Sept. 2017].
[3] D. Semënov, G. Mirzaeva, C. D. Townsend, G. C. Goodwin, “A battery storage control scheme for AC microgrids”, *20th Inter. Conf. on Electrical Machines and Systems (ICEMS)*, 2017, pp. 1-6.
[4] G. Coppez, “Review of battery storage optimisation in Distributed Generation”, *Proc. Power Electronics, Drives and Energy Systems (PEDES)*, 2010, pp. 1-6.
[5] Y. Zhang, T. Zhang, R. Wang, Y. Liu, B. Guo, “Optimal operation of a smart residential microgrid based on model predictive control by considering uncertainties and storage impacts”, *Solar Energy*, vol. 122, pp. 1052-1065, 2015.
[6] M. R. Sarker, “Optimal operation of a battery energy storage system: Trade-off between grid economics and storage health”, *Electric Power Systems Research*, vol. 152, pp. 342-349, 2017.
[7] A. Parisio, E. Rikos, L. Glielmo, “A Model Predictive Control Approach to Microgrid Operation Optimization”, *IEEE Trans. on Control Systems Technology*, vol. 22, pp. 1813-1827, 2014.
[8] M. Herceg, M. Kvasnica, C. N. Jones, M. Morari, “Multi-parametric toolbox 3.0”, *European Control Conference (ECC 2013)*, 2013, pp. 502-510.
[9] L. G. Meegahapola, D. Robinson, A. P. Agalgaonkar, S. Perera, P. Ciufo, “Microgrids of Commercial Buildings: Strategies to Manage Mode Transfer From Grid Connected to Islanded Mode”, *IEEE Trans. on Sustainable Energy*, vol. 5, pp. 1337-1347, 2014.
[10] Endeavour Energy, “Network Price List 2016/2017”, Available: http://www.endeavourenergy.com.au/, [Accessed September 2017].
[11] M. Herceg, M. Kvasnica, M. Morari, S. Gaulocher, J. Poland, *HYSDEL 3.0 – Manual*.
[12] A. Bemporad, "Model Predictive Control design: New trends and tools”, *Proc. of the IEEE Conf. on Decision and Control*, 2006, pp. 6678-6683.